ETL-0287

AD A116771

A general climatological guide to daily freezing conditions: frost days, ice days, and freeze-thaw days

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APRIL 1982

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ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA 22060

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ETL-0287	2. GOVT ACCESSION NO. AD-A116771	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A GENERAL CLIMATOLOGICAL GUIDE TO DAILY FREEZING CONDITIONS: FROST DAYS, ICE DAYS, AND FREEZE-THAW DAYS		5. TYPE OF REPORT & PERIOD COVERED Final Report July 1978 – July 1980 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ruth L. Wexler		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Engineer Topographic Laboratories Fort Belvoir, VA 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 4A161102AT24/C/001
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer Topographic Laboratories Fort Belvoir, VA 22060		12. REPORT DATE April 1982 13. NUMBER OF PAGES 49
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) U.S. Army Cold Regions Research and Engineering Laboratory Hanover, NH 03755		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Daily Maximum Temperatures
Daily Minimum Temperatures
Diurnal Freeze-Thaw
Diurnal Temperature Range
Freeze-Thaw Cycles
Frost Days
Ice Days

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Climatological information concerning daily freezing conditions is of considerable interest to military and civilian communities because of the impact of such conditions on traffic mobility, personnel performance, and equipment function. In support of strategic planning, this report presents a series of maps showing the geographical distributions of the annual incidence of frost days, ice days, and freeze-thaw days, respectively, over an extensive area of the Northern Hemisphere (Europe and U.S.S.R.). In addition, a number of simple climatological guides are provided whereby the above parameters, if required, might be conveniently derived from ordinarily available data, either for a given area or a single station.

SUMMARY

The geographical distributions of the annual incidence of frost days, ice days, and freeze-thaw days, respectively, have been presented in the form of a series of maps (figures 2, 3, and 4) for Europe and western U.S.S.R. The results show that away from the coast, the annual frequencies of frost days and ice days tend to decrease with latitude, whereas the incidence of freeze-thaw days is more erratic – generally greatest in the mid-latitudes, eventually decreasing toward the Pole and the Equator.

Various practical engineering guides, both graphical and mathematical, have been provided whereby the different freezing conditions (frost days, ice days, and freeze-thaw days) per given interval of time might be readily derived from routine climatological data. A particular effort has been made to consolidate or generalize the results so that (as for monthly data) a single graph (figure 8) for a given location appears to have broad applicability. Nevertheless, special studies are needed for climatic extremes, as in stations at or near the Arctic and Antarctic Circles or in coastal or mountainous localities.

On the whole, for much of the globe, freeze-thaw diurnal cycles are not derived from mean temperatures alone. Usually information on the mean daily maximum and the mean daily minimum temperatures is required. Based on long term observations, however, a few station models were developed whereby the monthly freeze-thaw diurnal cycles over the year could be estimated from the mean monthly temperature, as from figure 12 or equation (4). Such models are not as reliable for operational use as those requiring maximum and/or minimum temperatures.

Because of the physical contraints associated with freeze-thaw, attempts in the past to relate freeze-thaw cycles directly to mean temperatures have usually not met with success. It is hoped, therefore, that the various models provided in this report help explain the relationship of these cycles to the corresponding temperature regimes, not only for purposes of logistics and design but also as an aid to bioclimatology or to the understanding of periglacial activity.

PREFACE

The impetus for an investigation of the world-wide incidence of daily freezing conditions, especially diurnal freeze-thaw cycles, was generated by requests from several Army agencies, including the Test and Evaluation Command (TECOM). Freeze-thaw cycles have numerous applications of military significance, particularly with regard to off-road mobility, vulnerability of roofing, and equipment malfunction. Climatological studies of this nature provide weather support for Field Army tactical operations.

This work was accomplished under Project 4A161102AT24, Task C, Work Unit 001, "Relationship between Environmental Factors and Materiel Design Problems."

Appreciation is extended to the Environmental Technical Applications Center, Asheville, N.C., for providing processed data for several hundred stations in the Northern Hemisphere; to Alma Missouri, ETL, for computational assistance; to Cedric Key, ETL, for drafting and cartography; and to all colleagues in the Environmental Effects Group for their helpful suggestions.

The work was performed under the supervision of H. S. McPhilimy, Group Leader, Environmental Effects Group (EEG); M. Gast, Chief, MGI Systems Division; Dr. Thomas Niedringhaus, Acting Group Leader, EEG; Dr. Donald Dery, Chief, EEG; and Kent T. Yoritomo, Director, Geographic Sciences Laboratory.

COL Edward K. Wintz, CE was Commander and Director and Mr. Robert P. Macchia was Technical Director of the U.S. Army Engineer Topographic Laboratories during the report preparation.

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INTRODUCTION

The primary purpose of this report is to present the geographical distribution of the annual incidence of frost days, ice days, and freeze-thaw days, respectively, over an extensive area of the Northern Hemisphere, i.e., Europe and western U.S.S.R. A secondary objective is to provide simple graphical and mathematical aids whereby such daily freezing conditions may be estimated for any interval of time (as a year, a month, or a season) from routine climatological data. Daily freezing conditions may be defined as follows: Frost days are those days with minimum daily temperatures $\leqslant$ 0° C, ice days are those days with maximum daily temperatures $\leqslant$ 0° C, and freeze-thaw days are those with minimum daily temperatures $\leqslant$ 0° C and with maximum daily temperatures $>$ 0° C. Particular emphasis is directed toward the derivation of diurnal freeze-thaw cycles, a parameter not usually listed in climatic summaries. A given number of freeze-thaw days may represent different combinations of frost days and ice days. It is necessary therefore to understand the relationship among all three parameters.

The frequency of the various daily freezing conditions is of particular importance to the military because of the impact on field operations, transportation, and equipment performance. For example, during a bridging exercise of armed forces in Germany in the winter, a spray of water onto the deck suddenly iced over, producing treacherous footing.[1] Moreover, during a "free play" maneuver in the same period, wheeled vehicles became immobilized in a mixture of ice and mud caused by an unexpected thaw. The field operations had to be cancelled in each case. Another problem is that water from heavy rains accumulates in equipment and freezes, causing malfunction. Entrapped water, on freezing, produces pressure in all directions, creating havoc not only with equipment but also with roads, roofs, and many other structures. The frost upheaval of roads in the mid- to high latitudes has been studied extensively by departments of transportation (see Moulton, 1964 and Aldrich 1956 listed in References) throughout the United States and elsewhere.

[1]Ronald Liston and Gregory Wojtkun, Cold Regions Research and Engineering Laboratories (CRREL) 1979: Communication (unpublished) notes on a trip to Germany, Jan–Feb 1979.

A recent analysis of pothole formation was carried out to determine the extent to which diurnal freeze-thaw cycles were responsible. Hershfield found that the unusually large number of potholes on the roads in the eastern United States after the severe winter of 1977 – 1978 may have been due to the sequence of extensive rain followed by prolonged cold and eventual thaw, rather than just the frequency of the diurnal freeze-thaw cycles.[2] The amount of available moisture is of course a crucial factor in any consideration of the damaging effects of temperature fluctuations through 0° C.

Freeze-thaw is also of interest to the geologist, the hydrologist, and the agriculturist (see Washburn, 1973, listed in References). In some localities, as noted by Troll at El Misti, Peru, in the tropical highlands, these cycles may occur almost every day all year owing to rapid radiational cooling at night and intensive insolation by day.[3] Such action causes the soil to break up continuously, preventing seeds from rooting and thus limiting ground cover. Resulting problems of concern are surface run-off, erosion, flooding, and the bearing strength of the soil, all of which affect the military in a variety of ways, especially regarding mobility.

Inasmuch as a great deal of hazardous frost action affects the ground, knowledge of surface or ground temperatures would be highly useful; however, ground temperatures are not routinely reported. Various methods have therefore been employed to compensate for ground-air temperature disparities, a subject to be considered briefly later in this report. Unless otherwise stated, the temperatures referred to in this study have been obtained from observations taken in standard weather shelters at 1.5 to 1.8 m above ground (screen height).

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[2]David Hershfield, "Freeze-Thaw Cycles, Potholes, and the Winter of 1977–78," *Journal of Applied Meteorology*, Vol. 18, No. 8, 1979, pp. 1003–1007.

[3]C. Troll, *Structure Soils, Solifluction, and Frost Climates of the Earth, SIPRE Translation 43,* 1958, p. 121.

BACKGROUND

Previous investigators not only have produced maps showing the location to the freezing isotherm (0° C) over the surface of the globe or sections thereof per month or season, (Guttman 1961, Essa 1969, HQs AAF 1942) but also have presented the geographical distributions of diurnal freeze-thaw cycles per year for a number of different countries or areas, including the United States, Canada, Poland, Japan, and the Arctic. The References section, page 37, provides bibliographic data for specific reports. In certain of these earlier reports, freeze-thaw cycles were determined for specified temperature spans other than just across the freezing level – for example, –2° to 0° C (Russell, 1943); –2.2° to 1.1° C (Hastings, 1961); –6.7° to 10° C (Visher, 1945). A detailed regionalization of monthly freeze-thaw was carried out by Williams for the United States and Canada.[4] Annual patterns of monthly freeze-thaw are likewise categorized in this report, but only for broad temperature regimes (table 1).

Annual or monthly frequencies of frost days, ice days, or freeze-thaw days, respectively, were sometimes correlated with specific climatological parameters or indices. Shitara showed a linear relationship between the number of frost days and the mean daily minimum temperature as well as between the number of ice days and the mean daily maximum temperature for a network of stations in Japan for January and March.[5] He also produced a monthly graph in which diurnal freeze-thaw cycles might be derived directly from the corresponding mean daily maximum and minimum temperatures for a given station. Hershfield, who developed a similar graph based on monthly data for a network of stations in the United States, provided in addition a series of station models based on annual data whereby the incidence of freeze-thaw cycles was shown for different combinations of mean daily maximum and minimum temperatures.[6] Fraser related annual freeze-thaw incidence in Canada directly to mean diurnal temperature range.[7]

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[4] L. Williams, "Regionalization of Freeze-Thaw Activity," *Annals Amer. Assoc. Geog. 14*, 1964, pp. 597–611.

[5] H. Shitara, "On Winter Days and Ice Days in Japan," *Japanese Progress in Climatology*, 1970. pp. 85–99.

[6] David Hershfield, "An Investigation into Frequencies of Freeze-Thaw Cycles." Master's Thesis University of Maryland, 1973.

[7] J.K. Fraser, "Freeze-Thaw Frequencies and Mechanical Weathering in Canada," *Arctic* Vol. 12, 1959, pp. 40–52.

TABLE 1. Categories of Freezing Conditions Relative Frequencies Among Frost Days, Ice Days, and Freeze-Thaw Days Per Year (or Season, or Month)

Class	Frost Days	Ice Days	Freeze-Thaw Days
A	100%	100%	0%
B	100%	Variable	Variable
C	Variable	Variable	Variable
D	Variable	0%	Variable
E	0%	0%	0%

DATA

Most of the data in this report for Europe, the Soviet Union, and selected stations elsewhere are either based on direct observations of frost days and ice days listed in various foreign-language publications (see data bibliography) or determined from over 200 N-summaries of temperature distributions supplied by the U.S. Air Force Environmental Technical Applications Center (ETAC). For each weather station, a pair of N-summaries gives monthly and annual distributions of the daily maximum and minimum temperatures respectively (see appendix A for locations of various weather stations).[8] Frequencies of frost days and ice days then had to be computed from the appropriate temperature distributions. Periods of observations varied greatly among the different sources, from a few years for some of the ETAC stations to as many as 80 years for the German stations. Except for the ETAC stations, the data consisted of mean daily maximum and mean daily minimum temperatures as well as average numbers of frost days and ice days for the corresponding month or year. In some instances, the data for either frost days or ice days were not necessarily coincident with the temperatures. In all cases, frequencies of freeze-thaw days represent the differences between the corresponding frequencies of frost days and ice days.

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[8] U.S. Naval Weather Service Command. *Guide to Standard Weather Summaries and Climatic Services*, 1973, pp. 1-73, 1-74.

In the data analyses, a basic assumption is that the mean daily temperature represents the average of the daily maximum and minimum temperatures. A graphical definition of diurnal freeze-thaw, based on the above assumption, is given in figure 1, a daily freeze-thaw nomogram. It is seen in figure 1 that freeze-thaw is theoretically possible on any day when the daily mean temperature, x, for a given diurnal temperature range, y, is such that $-0.5y < x < 0.5y$ (° C), i.e., when the coordinates x and y both fall within the V-shaped area. This area is confined by the freeze-limit line ($y = 2x$) and the thaw-limit line ($y = -2x$): areas to the right of the V-shaped area are too warm for freezing; areas to the left are too cold for thawing.

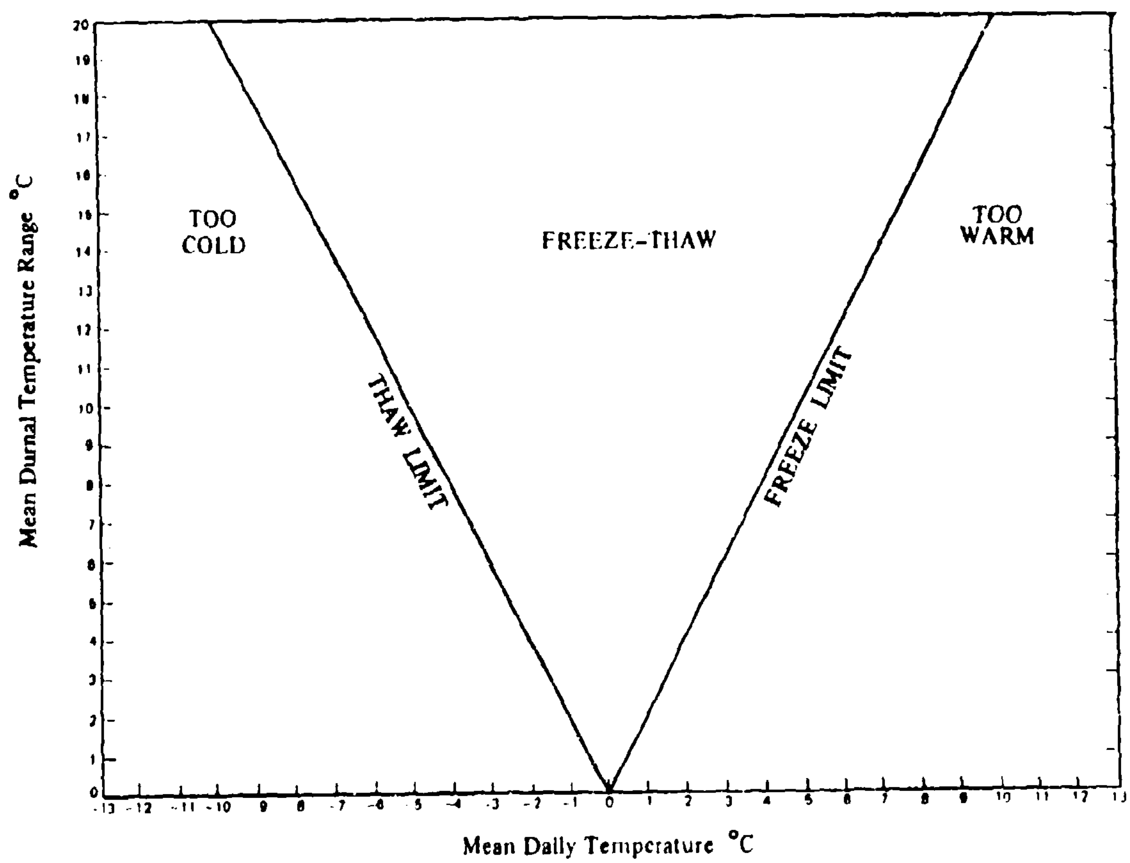
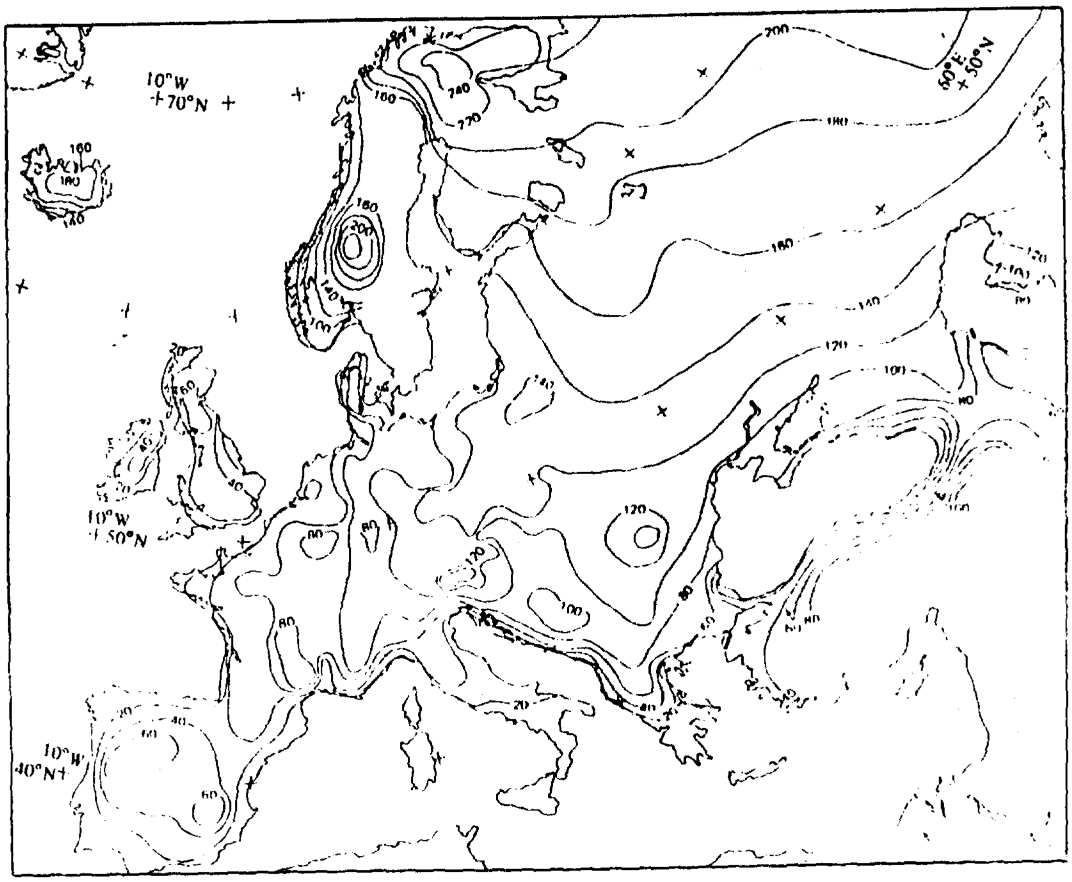


FIGURE 1. Daily Freeze-Thaw Nomogram.

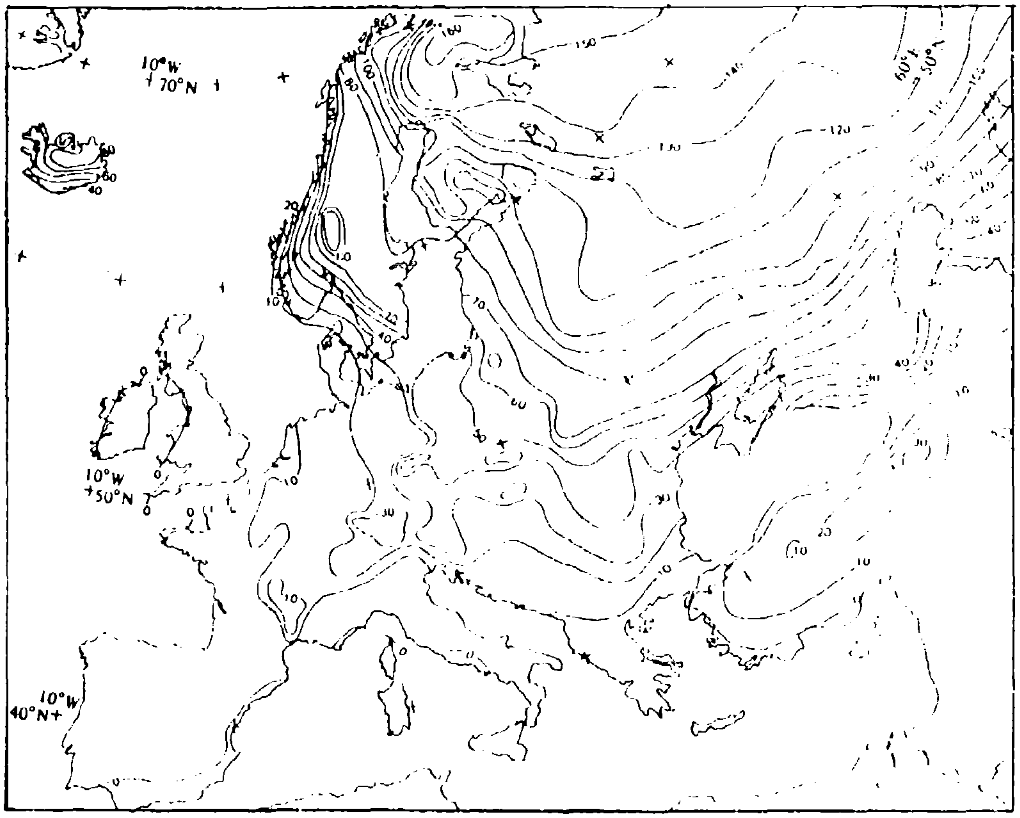
THE GEOGRAPHIC DISTRIBUTIONS OF DAILY FREEZING CONDITIONS PER YEAR OVER EUROPE AND WESTERN U.S.S.R.

The geographical distributions of various freezing conditions are presented for Europe and western U.S.S.R. in a series of maps (figures 2 to 4). Annual frequencies of frost days, ice days, and freeze-thaw days are shown respectively in figures 2, 3, and 4. Data from more than 1000 stations are included. Because of the relatively high incidence of frost days compared to the other two parameters, the adjacent isopleths in figure 2 represent a spacing of 20 days, whereas the spacing is only 10 days in figures 3 and 4.



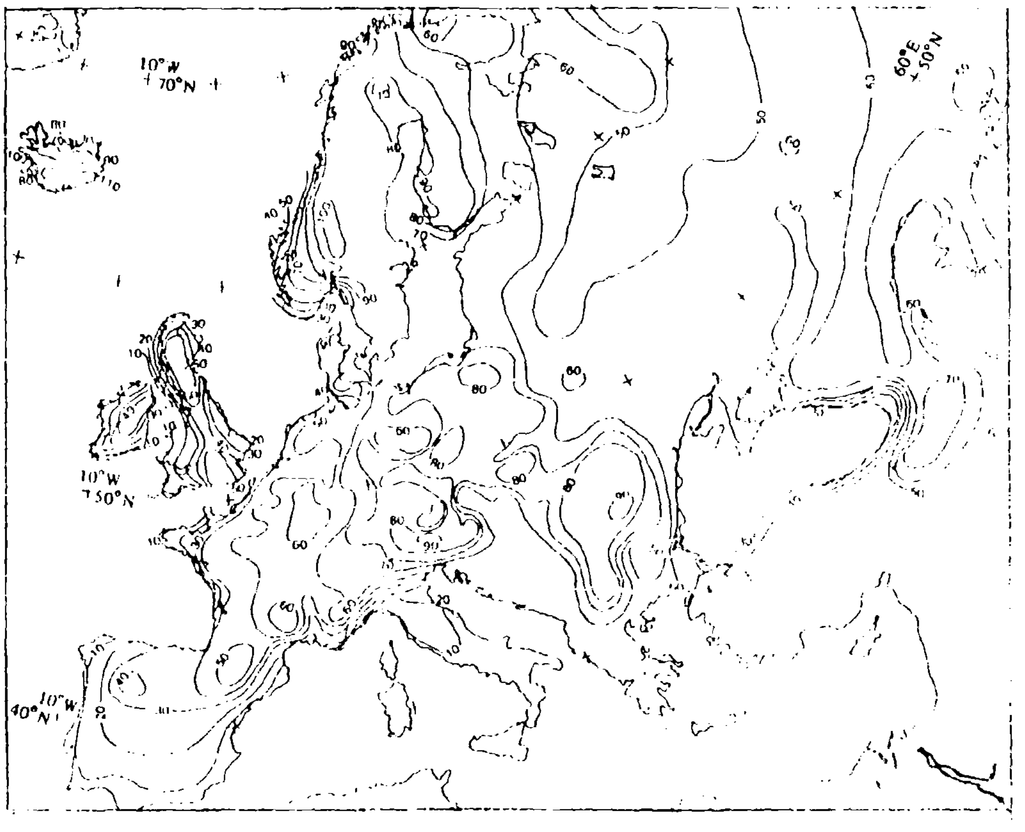
Note: Data for Sweden missing.

FIGURE 2. Annual Number of Frost Days: Europe and Western U.S.S.R.



Note: Data for Sweden missing.

FIGURE 3. Annual Number of Ice Days: Europe and Western U.S.S.R.



Note: Data for Sweden missing.

FIGURE 4. Annual Number of Freeze-Thaw Days: Europe and Western U.S.S.R.

In general, near the coast, maritime influence appears to be the primary factor responsible for the distribution patterns in the cited figures, with latitude the main factor inland. Oceanic effects are particularly marked in Norway, where the isopleths in all three cases parallel the coastline. Away from the coast, especially in the U.S.S.R., both frost days and ice days increase with latitude. Freeze-thaw days, however, tend to have relatively low incidence at very high latitudes (except at some coastal or island stations), increasing toward mid-latitudes, a pattern also observed in North America (see Fraser, 1959 listed in References). The map of ice days (figure 3), somewhat similar to that of frost days (figure 2) in overall pattern, has decidedly lower frequencies, and the ice days eventually diminish in the warmer climates of the British Isles and the Mediterranean countries. For such areas – that is, where there are essentially no ice days – the frequency of freeze-thaw days is equivalent to that of frost days.

If the map in figure 4 were extended northward to the Pole, freeze-thaw frequencies would reach zero in limited areas. Only stations in central Greenland or on the ice cap near the North Pole remain frozen at the surface all year. Even at northern coastal stations, although there may be no completely frost-free months, frost periods are intermittent. On the average the number of frost days along the Greenland coast is about 200-300/year and the number of ice days is about 100-200/year.[9] In the Antarctic, some stations which remain frozen all year are Halley, Byrd, McMurdo, and Vostok; those with some diurnal thawing in the summer months are Showa, Mirnyy, and Dumong D'Urville.[10]

The progression of annual freezing conditions from high to low latitudes may be broadly categorized, as in table 1, with class A too cold for freeze-thaw and class E too warm. Class B, with variable ice days but 100% frost days, is highly limited in area, encompassing the mentioned stations in the Arctic and the Antarctic. Class C represents most mid-latitude stations with variable numbers of frost days and ice days, and class D consists of mid- to low-latitude stations, with some "night-frost," but no ice days. Class E categorizes tropical stations, within the latitude belt 25° N to 25° S, where except for the highlands neither frost days nor ice days would be expected.

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[9] S. Orv., Ed., "Climates of the Polar Regions," *World Survey of Climatology*, Vol. 14. 1970. p. 95.

[10] U.S. Central Intelligence Agency, National Foreign Assessment Center, Polar Regions Atlas, 1978.

Table 1 provides a clue to the parameters that might be required for estimating freeze-thaw days. For instance, for those areas where the number of ice days is nil (class D), only statistical information on the daily minimum temperatures is required for estimating daily freeze-thaw cycles. On the other hand, for those areas with 100% frequency of frost days but with a variable number of ice days (class B), only information on the daily maximum is required (% freeze-thaw days = 100% - % ice days). For selected stations in the United States, Hershfield found relatively good correlation between the annual number of freeze-thaw days and the mean daily minimum temperature.[11] Evidently, for those stations the frequency of ice days was relatively low. Table 1, which depends essentially on the temperature regime, may be utilized for any interval of time, as a season or a month (for monthly data in the mid-latitude, classes A & B would correspond to winter; C & D to winter, spring, or autumn; E to summer). This table helps explain some of the problems associated with past attempts to correlate diurnal freeze-thaw activity with mean temperature alone (see Washburn, 1973 listed in References).

GENERAL CLIMATOLOGICAL MODELS

Although frequency information on daily freezing conditions may be available (figures 2 to 4), it is nevertheless highly useful for purposes of planning or design to be able to correlate such conditions with ordinary climatic parameters. Relationships thus determined also serve as practical tools for filling in missing data or assessing periglacial activity or bioclimatic limits. A variety of graphical and mathematical aids have accordingly been developed, in some cases parallelling those presented earlier (see Shitara, 1970; Fraser, 1959; and Hershfield, 1973 listed in References). An effort has been made in this study, however, to consolidate or generalize the results as well as to introduce new end products or new models. Quantitative procedures are offered to the extent possible.

[11] David Hershfield, "An Investigation into Frequencies of Free-Thaw Cycles." Master's Thesis, University of Maryland, 1973.

Annual Models. For networks of weather stations in various parts of the Soviet Union (see figure 5 for areas) as well as for Germany, the mean annual daily minimum temperatures (X_n) were plotted per the annual number of frost days (Y_n), and the mean annual daily maximum temperatures (Y_m) were plotted per the annual number of ice days (Y_m).

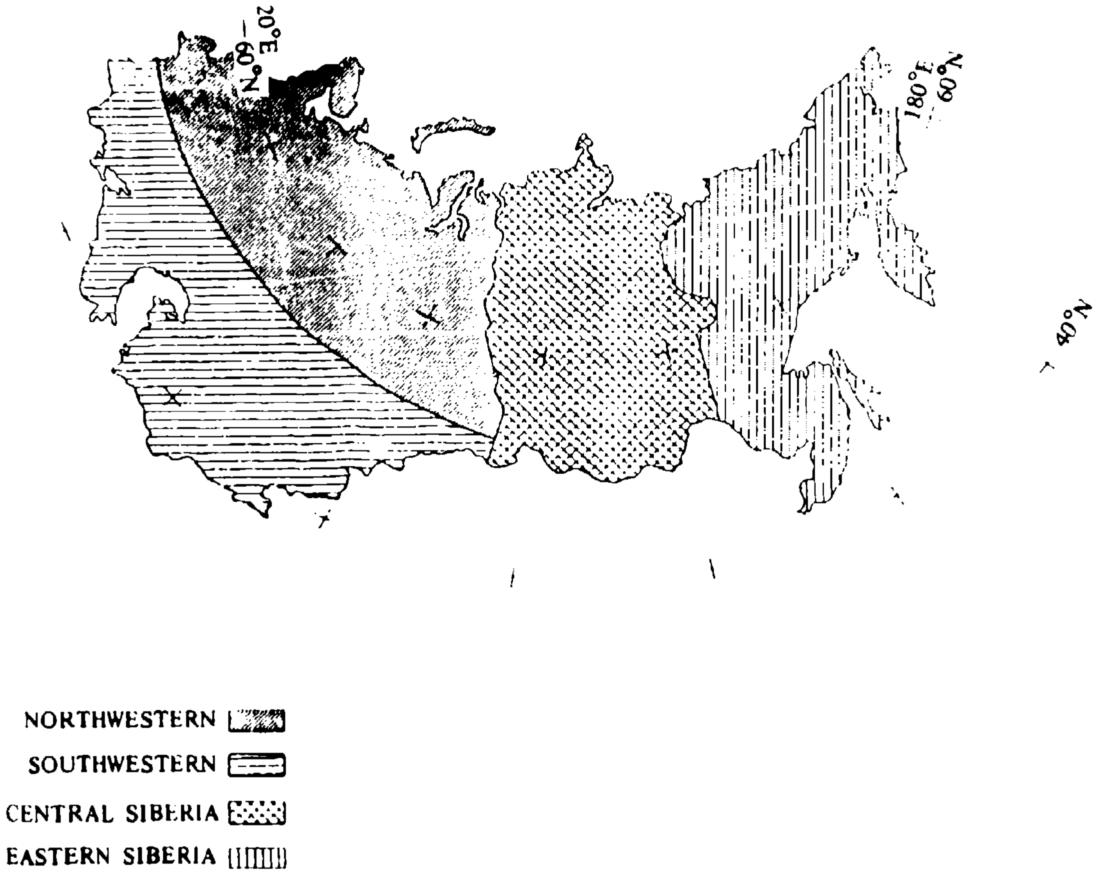

FIGURE 5. Areas of the Soviet Union.

It is seen in figure 6 for eastern Siberia that the plots for both pairs of parameters appear to form a nearly continuous line. Other plots (not given) for northwestern and southwestern U.S.S.R. as well as for central Siberia also showed similar trends, whereas for Germany (figure 7) the two regression lines are more distinct. For all these areas, linear regression equations were obtained of the form

$$y = \underline{a} + \underline{b}\,x \tag{1}$$

or

$$Y_n = \underline{a} + \underline{b}\,X_n \tag{1a}$$

and

$$Y_m = \underline{a} + \underline{b}\,X_m \tag{1b}$$

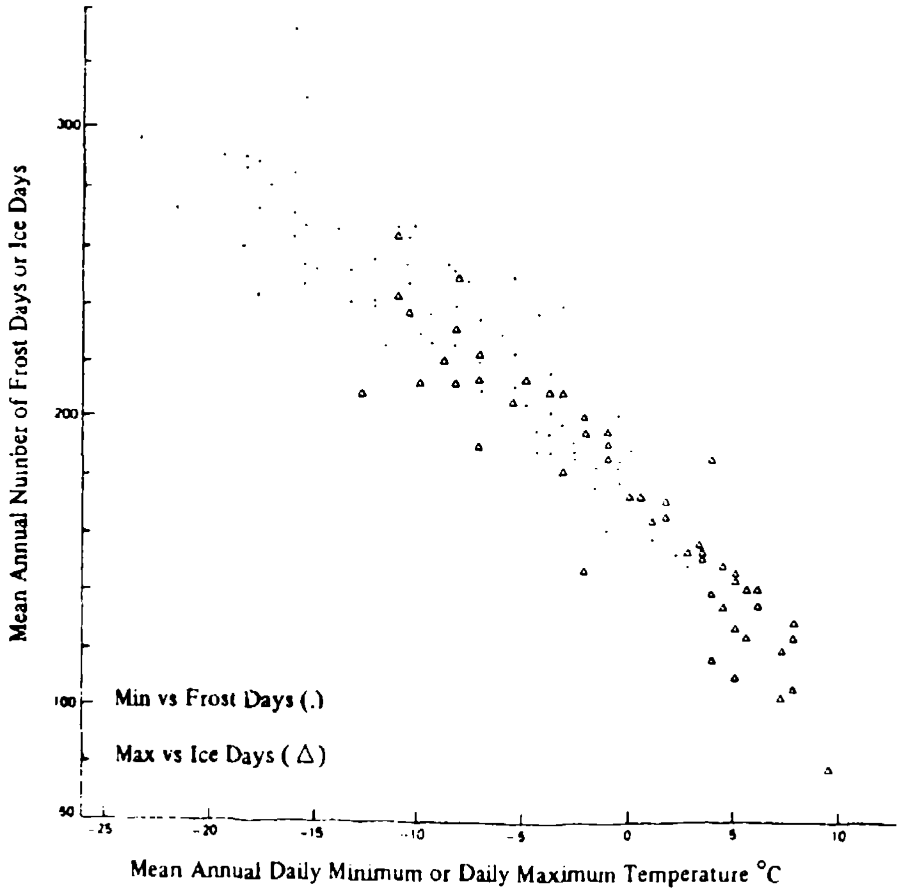

FIGURE 6. Mean Annual Number of Frost Days per Mean Daily Minimum Temperature, Mean Annual Number of Ice Days per Mean Daily Maximum Temperature: Eastern Siberia.

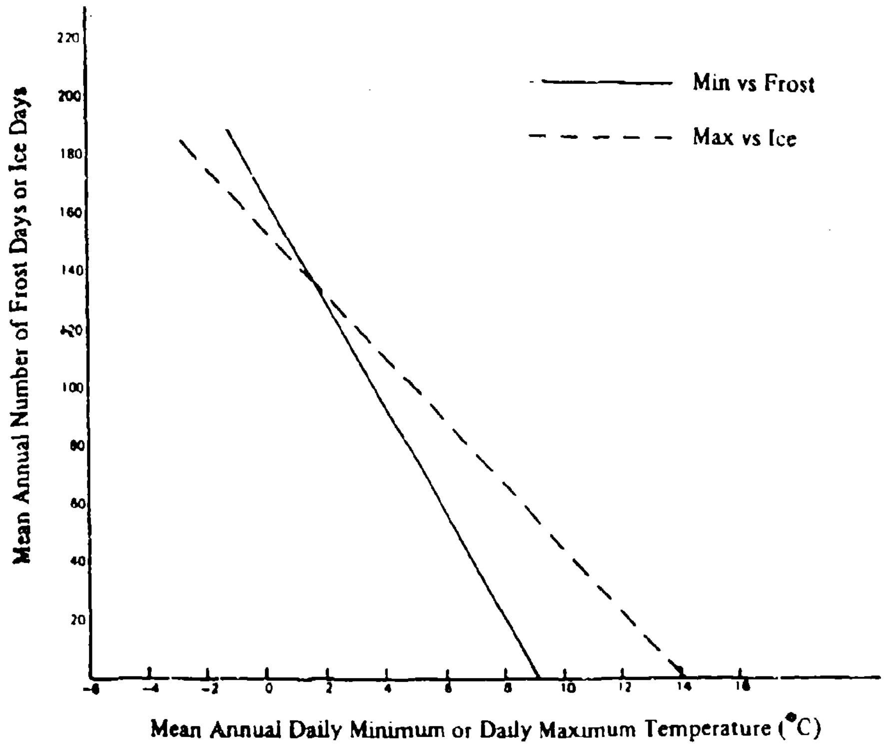

FIGURE 7. Mean Annual Number of Frost Days per Mean Daily Minimum Temperature, Mean Annual Number of Ice Days per Mean Daily Maximum Temperature: Germany.

where y = number of frost (ice) days
x = mean daily minimum (maximum)temp.,°C
$\underline{a}, \underline{b}$ = constants

if X_n = mean daily min, Y_n = number of frost days
X_m = mean daily max, Y_m = number of ice days

For example, for eastern Siberia, the annual number of frost days may be obtained from

$$Y_n = 182.9 - 5.6\,X_n$$

and the annual number of ice days from

$$Y_m = 167.4 - 6.1\,X_m$$

The corresponding number of freeze-thaw days per year, Z, then may be found from

$$Z = Y_n - Y_m \tag{2}$$

or for eastern Siberia

$$Z \approx 15.5 + 6\,(X_m - X_n) \tag{2a}$$

The above result is somewhat similar to that obtained for Canada by Fraser, who also found that the annual number of freeze-thaw days could be correlated directly with the mean annual diurnal temperature range.[12] However, his study was based on the transition zone of −2°C to 1°C.

Constants for equations (1a) and (1b) were likewise determined for other sections of the Soviet Union (central Siberia, northwestern U.S.S.R., and southwestern U.S.S.R.) as well as for Germany (figure 7). In table 2, the constants a and b, are listed for the appropriate linear equations for each of the above areas. It is noted in table 2 that the value of b increases with increasing continentality from west to east, i.e., from Germany to Siberia. On the whole, the linear fit gradually deteriorates as temperatures depart from 0°C. Possibly a power or log equation would be more appropriate beyond ±15°C.

From the plots of the regression lines for the German stations (figure 7), the annual frequencies of both frost days and ice days were estimated; then freeze-thaw days were computed for a number of test stations. A comparison of estimated and observed frequencies of all these parameters is given in table 3. Deviations were generally ⩽ 10 days per year for at least two-thirds of all cases, the greatest single discrepancy being 21 freeze-thaw days for Hohenpeissenberg. Since the number of freeze-thaw days is dependent on the other two parameters, errors in both of these may compound (as for Hohenpeissenberg) or may counteract each other. Nevertheless, the technique appears to yield fairly reasonable order-of-magnitude estimates of freeze-thaw frequencies as well as of frost days or ice days.

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[12] J.K. Fraser, "Freeze-Thaw Frequencies and Mechanical Weathering in Canada," *Arctic*, Vol. 12, 1959, pp. 40–52.

TABLE 2. Constants for Equations (1a) and (1b): Annual Data

A. Equation (1a): $Y_n = a + b X_n$ *

AREA	CONSTANTS a	b	TEMPERATURE LIMITS (° C) for X_n
Germany (Table B2)	170	−18.0	− 1, 8
U.S.S.R.			
Southwest	165	−10.8	− 5, 9
Northwest	168	− 9.7	− 15, 3
Central Siberia	171	− 6.5	− 20, − 8
Eastern Siberia	183	− 5.6	− 22, 2

B. Equation (1b): $Y_m = a + b X_m$ †

AREA	CONSTANTS a	b	TEMPERATURE LIMITS (° C) for X_m
Germany (Table B2)	160	−11.0	0, 14
U.S.S.R.			
Southwest	196	− 9.1	3, 21
Northwest	186	− 9.2	− 10, 11
Central Siberia	174	− 6.4	− 15, 7
Eastern Siberia	167	− 6.1	− 13, 10

* Y_n = number of frost days, X_n = mean daily min, °C
† Y_m = number of ice days, X_m = mean daily max, °C

TABLE 3. Estimated and Observed Annual Frequencies of Frost Days, Ice Days, and Freeze-Thaw Days (German Stations)

WMO # 10xxx	Station	Mean Annual Daily Maximum Temperature °C	Mean Annual Daily Minimum Temperature °C	Annual Number of Frost Days East	Annual Number of Frost Days Obs	Annual Number of Ice Days Est	Annual Number of Ice Days Obs	Annual Number of Freeze-Thaw Days Est	Annual Number of Freeze-Thaw Days Obs
185	Griefswald	11.4	4.4	86	84	30	21	56	63
382	Berlin-Dahlen	12.6	4.4	86	90	16	23	70	67
453	Brocken	5.0	−0.3	172	184	100	101	72	83
343	Celle	12.5	4.4	86	85	15	20	71	65
113	Nordeney	11.2	6.0	56	54	32	12	24	42
224	Bremen	12.2	5.4	68	72	22	18	46	54
410	Essen	12.7	5.5	65	59	17	10	48	49
578	Fichtelberg	5.7	−0.8	181	181	93	101	88	80
934	Friedrichshafen	12.6	4.6	83	97	18	25	65	72
962	Hohenpeissenberg	9.7	2.8	115	133	49	46	66	87
866	Munchen	12.5	4.0	94	105	19	31	75	74
639	Darmstadt	13.6	5.6	66	72	8	15	58	57

Another direct estimate of annual freeze-thaw frequencies was obtained by Hershfield for selected stations in the United States by means of an index that he referred to as the "complement of the frost-free period." (Since the frost period may contain some frost-free days, the term "complement of the frost-free period" was used instead of the more conventional term "frost period.")[13] This period is supposedly the average number of days between the first day of frost in the autumn and the last day of frost in the spring (equivalent to the frost period). He showed a linear regression (graphic) between that index and the annual frequency of daily freeze-thaw cycles across the temperature interval $-0.5°$ to $0°$.

The frost period has also been employed as a climatological index for estimating daily freeze-thaw for a network of German stations (table A2), with the following results:

$$Z = .54\,D - 33 \qquad (r = .88) \tag{3}$$

where

D = duration of frost period in days

Z = annual number of freeze-thaw days.

This equation is not valid for stations in high latitudes or at high elevations where long and intense frost periods are too cold for thawing to occur.

Monthly (Seasonal) Models. As with the annual data (figures 6 and 7), the mean monthly number of frost days were plotted per mean daily minimum temperature, and the mean number of ice days were plotted per mean daily maximum temperature for each month, November through March, for the German stations (table A3). The constants for equations (1a) and (1b), where the variables now refer to monthly means, are given in table 4. For the temperature interval within $\pm 5°C$, encompassing the bulk of the data for either frost days or ice days, using equation (1)

[13] David Hershfield, "An Investigation into Frequencies of Freeze-Thaw Cycles," Master's Thesis, University of Maryland, 1973.

$$y = 13.4 - 2.4\,x.$$

If x = mean daily minimum temperatures (°C),
y = the number of frost days/month.

If x = mean daily maximum temperatures (°C),
y = the number of ice days/month.

TABLE 4. Constants for Equations (1a) and (1b): Monthly Data, Germany (see table A3)

A. Number frost days, y_n, per mean daily min °C, x_n: $y_n = \underline{a} + \underline{b}\,x_n$ (1a)

	CONSTANTS		TEMP LIMITS (for X_n)
	a	b	
Nov	13.7	−2.6	~ ± 5
Dec	13.3	−2.6	~ ± 5
Jan	13.3	−2.3	~ ± 5
Feb	12.5	−2.2	~ ± 5
Mar	13.7	−3.0	~ ± 5

B. Number ice days, y_m, per mean daily max °C, x_m: $y_m = \underline{a} + \underline{b}\,x_m$ (1b)

	CONSTANTS		TEMP LIMITS (for X_m)
	a	b	
Nov	5.5	−0.6	≤ 8
Dec	13.7	−2.3	~ ± 5
Jan	13.6	−2.3	~ ± 5
Feb	12.9	−2.1	~ ± 5
Mar	4.7	−0.5	≤ 10

Based on the data for the above German stations, figure 8 then consists of a consolidated curve (partly manual) for estimating frost or ice days for any month from November through March, given the required parameters, i.e., the corresponding mean daily minimum or maximum temperature. Using figure 8, estimates were made of frost days and ice days, with freeze-thaw days then determined in each case from the above parameters, for 27 stations (table A2) for the different months. The observed and the estimated freeze-thaw incidences were compared for November through March for these stations, the average deviations per month being respectively 1.0, 1.7, 1.4, 1.6, and 1.0 days. (Once the percentage of days is determined per 30-day month, the corresponding number of days per given month is computed on the basis of the actual number of days for that month.) In addition, estimated and observed monthly freeze-thaw days were compared for 10 widely scattered stations for all months of the year (table 5). For the latter cases the discrepancies were somewhat greater, as expected, although in only two instances (out of 60) were they as high as six (20 percent) days per month, with only about eight instances as high as three days (10 percent).

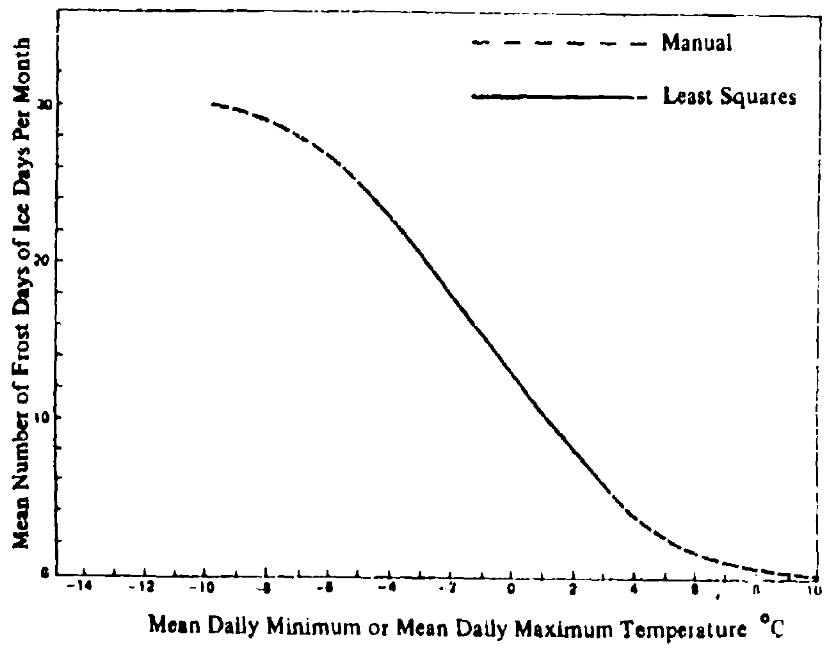

FIGURE 8. Mean Monthly Number of Frost Days per Mean Daily Minimum Temperature, Mean Monthly Number of Ice Days per Mean Daily Maximum Temperature: Germany, Consolidated Plot (November–March).

TABLE 5. Estimated and Observed Number of Days per Month of Freeze-Thaw: Selected Stations.

	Skopje, Yugoslavia		Lin-Yu, China		Dulles Airport, VA		Tehran, Iran		Flagstaff, AZ	
	Est	Obs	Est	Obs	Est	Obs	Est	Ob	Est	Obs
J	16	18	16	14	23	19	18	19	29	25
F	18	18	20	19	20	20	13	15	27	25
M	11	13	17	21	15	17	4	6	29	28
A	2	2	3	5	3	6	*	*	20	26
M	*	*	0	0	0	1	0	0	12	15
J	0	0	0	0	0	0	0	0	3	3
J	0	0	0	0	0	0	0	0	*	*
A	0	0	0	0	0	0	0	0	*	*
S	0	0	0	0	0	*	0	0	2	3
O	1	4	2	2	2	4	0	0	15	19
N	4	8	17	19	11	15	2	4	26	27
D	15	14	19	18	22	21	12	16	28	25

	Nord, Greenland		Verkoyansk, U.S.S.R.		Moscow U.S.S.R.		Praha, Czech.		Caribou, ME	
	Est	Obs	Est	Obs	Est	Obs	Est	Obs	Est	Obs
J	0	0	0	0	2	3	11	11	2	5
F	0	0	0	0	6	2	7	10	5	5
M	0	0	0	*	14	14	16	16	18	15
A	0	0	7	8	9	8	6	9	18	21
M	2	1	21	21	*	*	1	1	5	6
J	11	14	2	4	0	0	0	0	*	*
J	9	12	*	2	0	0	0	0	0	0
A	9	15	4	7	0	*	0	0	0	0
S	4	2	21	18	1	2	*	*	1	3
O	0	*	0	3	6	6	3	4	10	14
N	0	*	0	0	10	8	10	10	18	16
D	0	*	0	0	4	5	10	11	6	6

* = $\leqslant$ 0.5 days

Although the constants in table 4 were obtained from long-term data for a network of stations in a given area, a parallel investigation was also made for a single site, namely Zugspitze, Germany, a high elevation station (2692m). The data for this station were for a series of individual years, beginning in 1900 and continuing through 1950. At Zugspitze, peak freeze-thaw incidence occurs in the summer. Despite the differences in climatic conditions and data employment, constants similar to those in table 4 for the months of December, January, and February were obtained for Zugspitze for the months of June, July, and August.

Once the relationship between the mean daily minimum temperature and the number of frost days – as well as the relationship between the mean daily maximum temperature and the number of ice days – per a given interval of time has been extablished, it is possible to generate subsequent climatological guides. For instance, if figure 8 is used as a basis for monthly data, then figures 9 and 10 are examples of monthly freeze-thaw climatological guides that may be derived from such information. In figure 9 freeze-thaw incidence depends directly on the mean daily maximum and minimum temperatures, whereas in figure 10 freeze-thaw depends on the alternate parameters, mean daily temperature, and mean diurnal temperature range. Graphs somewhat similar to figure 9 have also been produced previously, the main difference being that both figure 8 and figure 9 represent averages for several months, whereas the earlier graphs were for either a specific month or a specific location.[14,15] Figure 10, a departure in format from the earlier models, follows the trend indicated in the daily freeze-thaw nomogram (figure 1).

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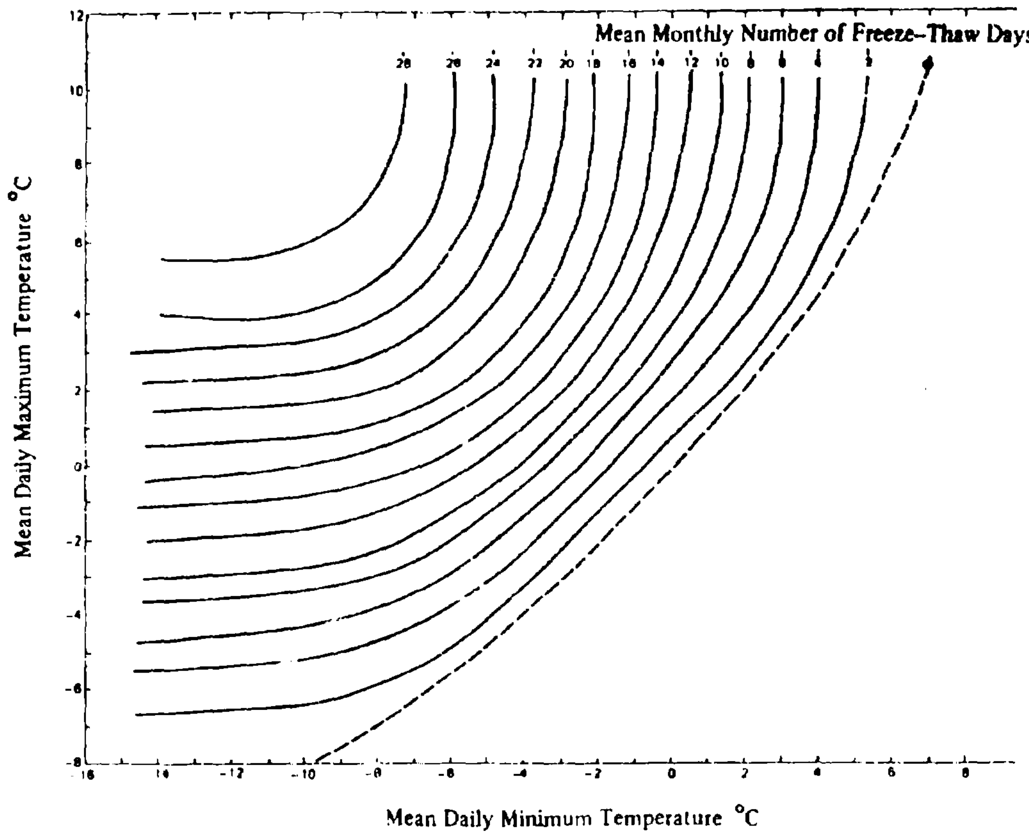
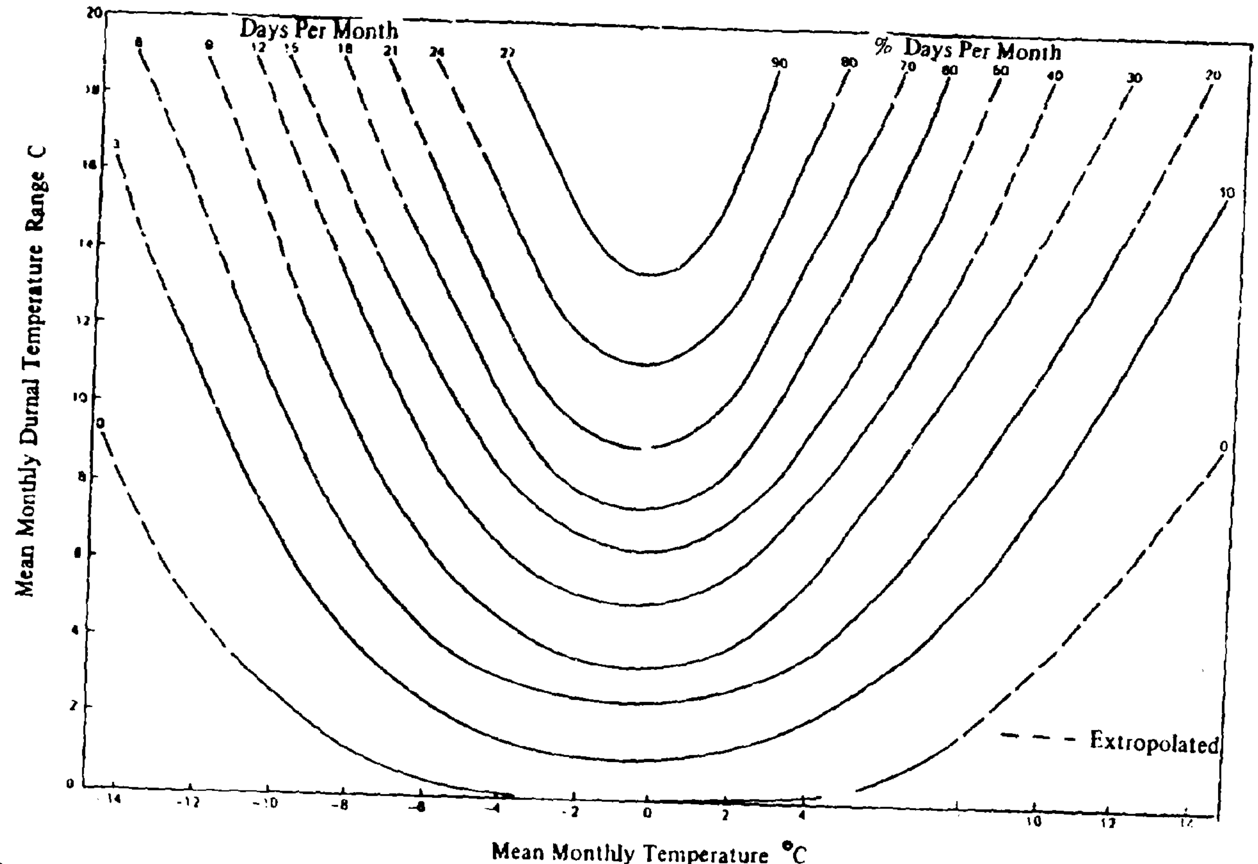
[14] H. Shitara, "On Winter Days and Ice Days in Japan," *Japanese Progress in Climatology*, 1970, pp. 85–99.

[15] David Hershfield, "An Investigation into Frequencies of Freeze-Thaw Cycles," Master's Thesis, University of Maryland, 1973.



Note: Computed on basis of 30-day month.

FIGURE 9. Mean Monthly Number of Freeze-Thaw Days per Mean Daily Maximum and Minimum Temperatures.



Note: Computed on basis of 30-day month.

FIGURE 10. Mean Monthly Frequency of Freeze-Thaw Days per Mean Daily Temperature and Mean Diurnal Temperature Range.

Station Models. A few station models of monthly freeze-thaw incidence per mean monthly temperature and mean diurnal temperature range throughout the year are given (figure 11) for the ready comparison of different climates. The following stations are included in figure 11: (A) Polar Station, U.S.S.R.; (B) International Falls, Minnesota; (C) Munchen, Germany; and (D) Fort Flatters, Algeria. It is seen that Polar Station (high latitude) is too cold to experience freeze-thaw in the winter. However, International Falls (highly continental) is subject to a double peak of freeze-thaw days, in the autumn and in the spring, whereas Munchen (moderate climate) has some diurnal freeze-thaw throughout much of the year except for the summer, i.e., from September to May. More limited freeze-thaw cycles are noted at Fort Flatters, Algeria, the low latitude desert station. In table 6, characteristics of the climate with respect to freeze-thaw diurnal cycles are given for selected sites, including those in figure 11.

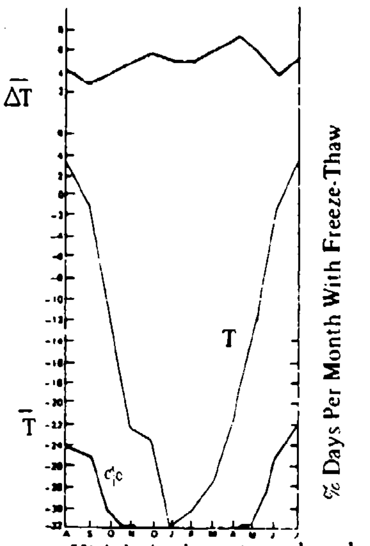
Another, perhaps more direct, way of comparing freeze-thaw temperature regimes is shown in figure 12, where freeze-thaw frequency per month is plotted directly against mean monthly temperature without regard to time of year. The plots in figure 12 are all somewhat smoothed. Appendix B contains examples of unsmoothed plots for two stations (figure B1). The station models in figure 12 were found to be represented by a single empirical equation, namely

$$y = a \sin Q \tag{4}$$

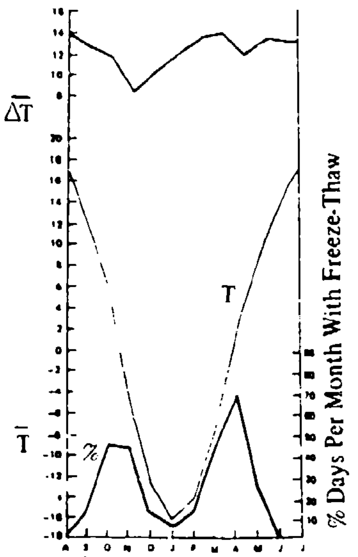
where

y = % days per month with freeze-thaw
a = amplitude of curve (peak % monthly freeze-thaw)
Q = $1.57\ (x + b)/b$
[Q in radians (1.57 = conversion factors)]
b = $|x_{y=a} - x_{y=o}|$

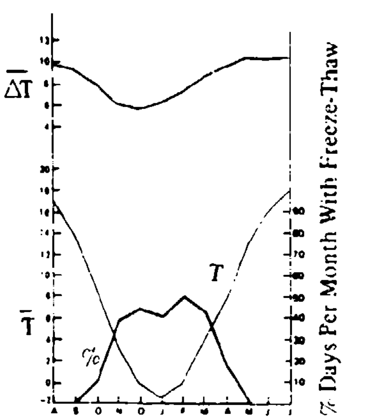
$x_{y=a}$ = temperature at peak % (usually 0° C), i.e., at $y = a$
$x_{y=o}$ = temperature at which freeze-thaw is nil = cut-off temperature, i.e., $y = o$
x = mean monthly temperature (°C)



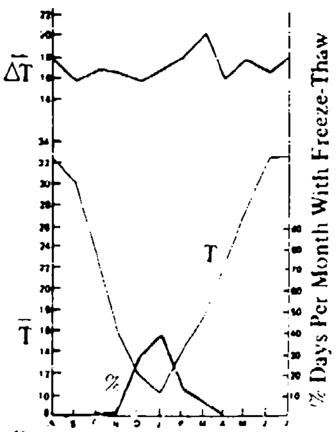
A. High-latitude, extremely cold
I. Polar Station U.S.S.R



B. Mid-latitude, highly continental
II. International Falls, Minn.



C. Mid-latitude, moderate climate
III. Munchen, Germany



D. Low-latitude, desert
IV. Fort Flatters, Algeria

Note:
$\overline{\Delta T}$ = Mean Diurnal Temperature Range °C
$\overline{T}$ = Mean Monthly Temperature, °C

FIGURE 11. Examples of Annual Patterns of Mean Monthly Freeze-Thaw Diurnal Cycles, Temperature, and Diurnal Temperature Range.

TABLE 6. Annual Patterns of Freeze-Thaw Diurnal Cycles: Peak Seasonal or Monthly Freeze-Thaw Diurnal Cycles per Latitude and/or Climatic Zone.

Pattern	Peak Season	Location	Characteristics	Sample Stations	Peak Month(s)		Av. No. Freeze-Thaw Days per Year
I	Summer	High Latitudes or high altitudes in mid-latitudes	Winter too cold for any thawing to occur	Polar Station, U.S.S.R.	Jul		52
				Nord, Greenland	Jun	Aug	45
				Zugspitze, Germany*	Jun		81
II	Spring and Autumn	High to mid-latitudes (Continental Stations)	Winter too cold for thaw, summer too warm for frost	Verkhoyansk, U.S.S.R.	May	Sept	64
				Alpena, MI	Apr	Nov	111
				International Falls, MN	Apr	Oct	84
III a.	Winter (Several Months)	Mid-latitudes	Nearly constant freeze-thaw frequencies for several months (moderate temperatures, mostly above 0° C to a few degrees below)	Munchen, Germany	Dec	Mar	71
				Boston, MA	Dec	Mar	72
b.	Single Month	Mid- to low Latitudes	Single, fairly sharp peak	Shanghai, China	Jan		44
				Tehran, Iran	Jan		59
IV	Variable	Low Latitude (desert or highlands)	Relatively high mean monthly temperatures (≥ 8°C) and high diurnal temperature range (≥ 15°C)	Flagstaff, AZ*	Nov	Apr	174
				Fort Flatters, Algeria	Jan		27

* > 2000 meters elevation

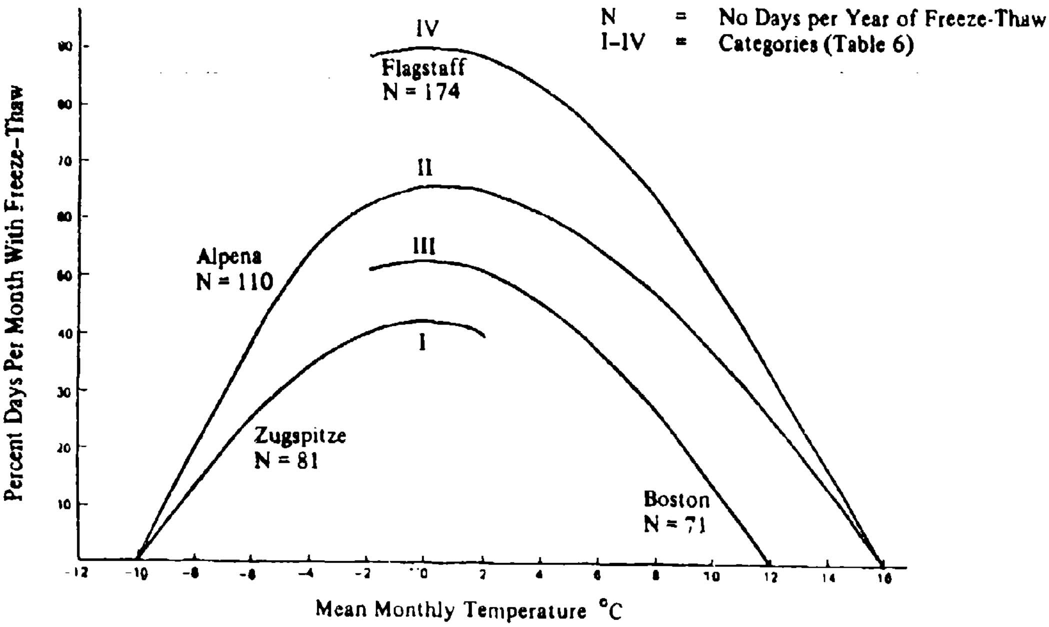


Figure 12. Percent Days per Month With Freeze-Thaw per Mean Monthly Temperature: Station Models (Smoothed Plots).

Table 7 lists values for a and b for equation (4) for selected stations, including those in figure 12. Figure B2 shows two examples of theoretical plots for given values of b and a range of values of a.

In some cases, a given model (as in figure 12) might serve a group of stations of similar climate. Expecially striking in this figure are the differences at a given temperature of the frequencies of freeze-thaw diurnal cycles for the different temperature regimes shown, i.e., Flagstaff (desert), Alpena (continental), Boston (moderate), Zugspitze (very cold). All the station models in figure 12 are based on long-term averages.

In the case of Zugspitze, since data were available, the mean monthly temperature was plotted per the percent frequency of days with freeze-thaw for a single month (June), year-by-year for a 50-year period. The result was indeterminate. On the other hand, separate plots for June of the mean daily minimum temperature per number of frost days and the mean daily maximum temperature per number of ice days provided relatively good linear relationships, as noted earlier.

TABLE 7. Constants for Equation (4)*: Stations in U.S. and Germany.

		Constants		Limiting Mean Monthly Temp for Freeze-Thaw Regime	
		a	b	Warmest (°C)	Coldest
USA	Dulles, VA	66	16	16	0
	Baltimore, MD	64	14	14	0
	Charleston, WV	57	16	16	0
	Boston, MA	53	12	12	– 2
	Alpena, MI	66	$b = 10,\ x > 0^\circ C$ $b = 16,\ x < 0^\circ C$	16	–10
	Flagstaff, AZ	90	16	16	– 2
Germany	Munchen	48	10	10	0
	Zugspitze	43	10	2	–10

*$y = a \sin Q$
Q (radians) $= 1.57\,(x + b)/b$
x = mean monthly temp, °C

GROUND FROST

Most investigators of diurnal freeze-thaw cycles, although analyzing temperature data at screen height (1.5 to 1.8m), have nevertheless been concerned with ground temperatures, data not routinely available. In order to allow for the invariably greater range of ground temperatures compared to air temperatures, freeze-thaw cycles have sometimes been based on relatively broad temperature zones, as mentioned (see Russell, 1943; Visher, 1945; and Williams, 1964 listed in References). In any case, various studies have been carried out to establish ratios between frequencies of freeze-thaw cycles at the ground and those of the air (see Wilson, 1969 and Washburn, 1973 listed in References). Often such ratios represent long-term averages.

In contrast to the above climatological means, a comparison was made of ground frost and air frost in Great Britain for a network of stations for the individual years 1957 and 1963, a relatively mild and an extremely cold year, respectively. The resultant ratios of ground frost over air frost are highly variable not only among neighboring stations but also at a single site for different times. While the ratios for the milder year of 1957 were generally higher than that of 1963, both ground and air were considerably colder in the latter year (with greater likelihood of low level inversions). Consequently an investigation of such ratios for different weather conditions is therefore indicated for operational needs. Moreover, since water is the basic ingredient for all frost, most important of all is a consideration of the prevalence of moisture in any form (dew, precipitation, run-off) either preceding or during frost occurrence.

CONCLUSIONS

It is concluded that

1. The climatic phenomenon of the diurnal freeze-thaw cycle has a number of military and civilian implications.

2. From annual data for a network of stations in a specified area, linear regression equations may be developed such that order–of–magnitude estimates of diurnal freeze-thaw cycles may be readily made for any other station in that area.

3. From monthly data in a given mid-latitude region, a variety of charts may be produced whereby diurnal freeze-thaw frequencies may be derived either from mean daily maximum and mean daily minimum temperatures or from the alternate set of parameters, namely mean daily temperature and mean diurnal temperature range: The results appear to have widespread applicability.

4. The need for synoptic studies is indicated, particularly of low level inversions, since the use of an established ratio of ground freeze-thaw diurnal cycles to screen height freeze-thaw diurnal cycles based on a long period of tim cannot be counted on for operational use.

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APPENDIX A. STATION LOCATION AND CLIMATOLOGICAL DATA.

TABLE A1. World-Wide Stations.

WOM 10XXX	Station Name	Altitude M	Latitude N	Longitude E	ANNUAL DAYS Frost (Min ≤ 0°C)	ANNUAL DAYS Ice (Max ≤ 0°C)	MEAN ANNUAL Daily Max(°C)	MEAN ANNUAL Daily Min(°C)
03204	Isle of Man,UK	17	54 05	−04 38	17.1	0.0	12.2	7.2
04030	Reykjavik,Iceland	18	64 08	−21 56	127.6	51.2	6.8	2.3
04063	Akureyri,Iceland	5	65 41	−18 04	159.1	72.7	6.4	1.0
04310	Nord,Greenland	36	81 36	−16 40	333.6	289.1	−13.7	−19.5
04320	Danmarkshavn,Greenland	18	76 46	18 46	326.5	267.2	− 9.0	−14.6
06011	Thorshavn,Faroe Isl.	24	62 03	−06 45	59.8	12.0	8.8	4.5
06265	Soesterberg,Netherlands	20	52 08	05 16	70.1	17.4	12.8	5.7
06589	Luxembourg,Luxembourg	330	49 37	06 03	82.0	22.1	13.2	5.5
06620	Bern,Switzerland	572	46 57	07 26	89.2	31.3	12.9	5.2
06670	Zurich,Switzerland	431	47 29	08 32	101.9	32.0	12.9	4.6
06700	Geneve,Switzerland	430	46 14	06 06	89.6	19.1	14.1	5.2
08094	Monflorite, Spain	540	42 05	−00 19	56.6	2.2	19.0	7.3
08180	Barcelona,Spain	95	41 25	02 09	3.1	0.0	19.7	13.2
08222	Madrid,Spain	610	40 30	−03 27	27.9	0.0	19.8	8.9
08285	Valencia,Spain	18	39 28	−00 23	2.1	0.0	21.9	12.5
08391	Sevilla,Spain	27	37 25	−05 54	6.4	0.0	24.7	11.9
08506	Horta,Azores	62	38 31	−28 38	0.0	0.0	20.1	15.7
08575	Braganca,Azores	718	41 39	−06 40	42.8	1.2	17.2	7.3
10147	Hamburg, Germany	16	53 38	10 00	84.1	27.5	12.3	5.3
10224	Bremen,Germany	04	53 03	08 47	80.8	24.2	12.9	5.4
10313	Munster,Germany	64	51 58	07 36	70.0	24.4	12.8	5.9
10384	Berlin,Germany	50	52 28	13 24	90.0	37.8	12.7	5.7
10637	Frankfurt,Germany	112	50 02	08 34	78.7	23.6	13.9	5.5
10763	Nurnberg,Germany	318	49 30	11 05	110.5	35.6	13.1	4.1
10866	Munchen,Germany	528	48 08	11 42	115.9	44.6	12.4	4.1

TABLE A1. World-Wide Stations. (Continued)

WOM 10XXX	Station Name	Altitude M	Latitude N	Longitude E	ANNUAL DAYS Frost (Min ≤ 0°C)	ANNUAL DAYS Ice (Max ≤ 0°C)	MEAN ANNUAL Daily Max(°C)	MEAN ANNUAL Daily Min(°C)
11036	Wien,Austria	193	48 07	16 34	97.9	37.7	13.9	5.6
11120	Innsbruck,Austria	598	47 16	11 21	137.8	29.3	14.2	2.9
11518	Praha,Czechoslovakia	374	50 06	14 17	121.3	50.3	11.9	3.8
12150	Gdansk,Poland	12	54 23	18 36	107.9	42.6	11.1	4.6
12375	Warsaw,Poland	107	52 11	20 58	125.3	54.2	11.6	3.7
12424	Wroclaw,Poland	124	51 06	16 53	123.8	38.6	12.9	3.6
12565	Krakow,Poland	237	50 05	19 48	137.6	48.3	12.1	3.1
12840	Budapest,Hungary	130	47 31	19 02	80.2	26.8	14.9	6.9
12882	Debrecen,Hungary	113	47 29	21 39	110.4	36.1	14.7	5.2
13274	Belgradc,Yugoslavia	78	44 49	20 25	82.9	24.3	16.5	7.1
13334	Split,Yugoslavia	49	43 30	16 27	9.2	0.9	19.6	13.1
13483	Skopje,Yugoslavia	240	41 59	21 28	95.5	16.9	18.2	6.3
15120	Cluj,Rumania	313	46 47	23 42	132.7	44.2	14.4	3.4
15420	Bucuresti,Rumania	92	44 29	26 08	108.3	34.5	16.3	5.8
15480	Constanta,Rumania	32	44 11	28 40	69.7	22.7	14.8	8.5
16100	Venezia,Italy	4	45 26	12 23	48.6	2.4	16.8	9.5
16120	Genova,Italy	3	44 25	08 51	6.7	0.8	18.2	12.4
16190	Ancona,Italy	105	43 37	13 31	7.2	0.4	17.5	12.3
16239	Roma,Italy	129	41 48	12 35	22.6	0.0	20.9	10.6
16289	Napoli,Italy	72	40 51	14 18	6.9	0.0	20.3	11.5
16560	Cagliari,Sardinia	18	39 15	09 03	3.9	0.0	20.8	12.2
17030	Samsun,Turkey	44	41 17	36 20	12.0	0.6	18.3	11.5
17050	Edirne,Turkey	48	41 40	26 34	60.0	8.1	19.2	8.3
17060	Istanbul,Turkey	27	40 58	28 49	28.5	3.8	18.4	10.4
17096	Erzurum,Turkey	1893	39 55	41 16	159.1	76.5	11.4	0.7
17129	Ankara,Turkey	806	39 57	32 41	101.5	17.0	18.1	5.0
17218	Izmir,Turkey	06	38 30	27 01	21.6	0.4	22.3	11.5
17350	Adana,Turkey	76	37 00	35 26	8.1	0.0	24.9	13.4
20476	Polar Station,U.S.S.R.	—	75 24	88 40	325.2	273.2	−11.9	−17.2
22550	Archangel,U.S.S.R.	13	64 35	40 30	202.3	143.2	4.2	− 2.7

TABLE A1. World-Wide Stations. (Continued)

WOM 10XXX	Station Name	Altitude M	Latitude N	Longitude E	ANNUAL DAYS Frost (Min ≤ 0°C)	ANNUAL DAYS Ice (Max ≤ 0°C)	MEAN ANNUAL Daily Max(°C)	MEAN ANNUAL Daily Min(°C)
23032	Marresale,U.S.S.R.	11	69 43	66 49	285.5	232.7	- 5.7	-11.5
23074	Dudinka,U.S.S.R.	28	69 24	86 10	266.6	233.4	- 7.2	-13.7
23330	Salekhard,U.S.S.R.	35	66 32	66 32	254.1	199.6	- 2.9	- 9.9
23518	Ust' Shchugor,U.S.S.R.	75	64 16	57 37	230.8	161.8	2.4	- 5.7
23849	Surgut',U.S.S.R.	43	61 15	73 30	224.3	161.8	1.9	- 6.2
24266	Verkhoyansk,U.S.S.R.	137	67 33	133 23	272.3	208.8	-10.4	-21.4
24959	Yakutsk,U.S.S.R.	103	62 05	129 45	245.8	189.8	- 5.4	-15.2
25551	Markovo,U.S.S.R.	33	64 41	170 25	265.2	208.5	- 3.6	-13.3
26063	Leningrad,U.S.S.R.	4	59 58	30 38	170.7	103.2	7.4	0.0
26850	Minsk,U.S.S.R.	234	53 52	27 32	149.1	101.2	9.1	2.5
27196	Kirov,U.S.S.R.	164	58 39	49 37	192.3	142.7	5.7	- 1.5
27612	Moskva,U.S.S.R.	156	55 45	37 34	157.3	110.3	8.6	1.6
28044	Serov,U.S.S.R.	132	59 36	60 32	210.5	139.4	5.7	- 3.8
28225	Molotov,U.S.S.R.	161	58 01	56 18	185.7	136.9	6.3	- 1.5
28440	Sverdlovsk,U.S.S.R.	237	56 48	60 38	206.3	134.4	6.4	- 2.8
28698	Omsk,U.S.S.R.	94	54 56	73 24	201.7	147.5	6.1	- 3.5
28722	Ufa, U.S.S.R.	197	54 45	56 00	186.0	127.8	7.6	- 1.1
29574	Krasnoyarsk,U.S.S.R.	194	56 00	92 53	206.4	141.9	5.4	- 3.7
30230	Kirensk,U.S.S.R.	261	57 46	108 07	236.4	160.7	1.7	- 9.9
30710	Irkutsk,U.S.S.R.	485	52 16	104 21	229.8	141.5	5.4	- 6.2
30925	Kyakhta,U.S.S.R.	789	50 22	106 27	220.6	142.6	5.6	- 5.4
31088	Okhotsk,U.S.S.R.	06	59 22	142 12	239.4	186.0	- 1.4	- 7.8
31735	Khabarovsk,U.S.S.R	72	48 31	135 10	186.4	136.4	6.3	- 2.6
31960	Vladivostok,U.S.S.R.	138	43 07	131 54	158.0	107.4	7.8	1.5
31969	Pos'yet,U.S.S.R.	16	42 39	130 48	153.0	81.6	10.5	2.7
32540	Petropavlovsk,U.S.S.R.	70	52 58	158 45	201.3	118.1	5.4	- 0.9
33393	L'vov,U.S.S.R.	325	49 49	23 57	131.5	70.6	11.4	3.5
34009	Kursk,U.S.S.R.	167	51 39	36 11	153.5	96.0	10.2	1.8
34172	Saratov,U.S.S.R.	156	51 34	46 02	159.5	115.7	9.7	2.7
34880	Astrakhan,U.S.S.R.	18	46 16	48 02	130.1	58.4	15.1	5.4

TABLE A1. World-Wide Stations.(Continued)

WOM 10XXX	Station Name	Altitude M	Latitude N	Longitude E	ANNUAL DAYS Frost (Min ≤ 0°C)	ANNUAL DAYS Ice (Max ≤ 0°C)	MEAN ANNUAL Daily Max(°C)	MEAN ANNUAL Daily Min(°C)
36231	Onguday,U.S.S.R.	—	50 45	86 09	221.8	127.7	6.9	− 6.2
37549	Tbilisi,U.S.S.R.	490	41 41	44 57	69.1	4.0	17.8	8.3
40007	Aleppo,Syria	392	36 11	37 13	30.8	0.2	24.3	10.9
40712	Rezaiyeh,Iran	1332	37 32	45 05	102.8	25.0	18.2	6.3
40754	Tehran,Iran	1196	35 42	51 21	63.8	4.6	22.2	10.6
40766	Kermanshah,Iran	1332	34 19	47 07	110.7	8.6	22.1	5.1
40800	Esfahan,Iran	1590	32 37	51 40	83.8	1.9	23.7	7.6
43540	Srinagar,Kashmir	1587	34 05	74 50	85.4	10.5	18.8	7.6
50953	Harbin,China	145	45 45	126 38	183.7	117.5	9.7	− 1.8
52889	Kao-Lan,China	1520	36 03	103 47	146.0	26.0	16.1	3.3
54342	Mukden,China	42	41 47	123 24	156.1	81.7	13.5	2.8
54449	Lin-Yu,China	27	40 00	119 44	138.6	41.3	15.2	5.5
54527	Tientsin,China	16	39 11	117 08	112.6	29.2	17.6	8.2
56778	Kun-Ming,China	1893	25 02	102 43	17.0	0.0	20.7	9.8
57494	Han-Kou,China	23	30 25	114 17	40.2	1.9	21.2	12.8
57993	Kan-Hsien,China	110	25 50	114 50	9.5	0.5	23.9	16.1
58367	Shanghai,China	5	31 12	121 26	45.2	1.7	19.9	12.6
60590	El Golea,Algeria	398	30 34	02 52	15.7	0.0	28.7	13.9
60608	Fort Flatters,Algeria	354	28 08	06 50	26.8	0.0	31.4	13.9
60620	Adrar,Algeria	264	27 53	00 17	10.0	0.0	32.8	15.5

TABLE A2. Germany, Network 1 (27 Stations)

STATION NAME	Altitude M	Latitude N	Longitude E	ANNUAL DAYS FROST (Min ≤ 0°C)	ANNUAL DAYS ICE (Max ≤ 0° C)	MEAN DAILY MAX (° C)	ANNUAL DAILY MIN (° C)
Klaussen	140	53 48	22 07	129.6	51.3	10.7	2.9
Tilsit	18	55 04	21 54	124.7	48.7	10.7	2.2
Bromberg	46	53 08	18 00	108.3	33.9	12.0	3.5
Konitz	175	53 42	17 34	123.3	44.0	10.8	2.9
Danzig	5	54 24	18 40	93.5	31.3	11.0	4.3
New Hammerstein	11	54 40	17 35	130.1	23.5	11.3	1.9
Stettin	36	53 23	14 38	80.8	28.2	12.0	4.6
Wyk	7	54 41	08 35	64.1	16.9	11.3	5.5
Brand	790	50 17	16 33	155.0	76.8	8.7	1.6
Glatzer Schneeberg	1215	50 12	16 50	181.6	107.2	5.6	−0.2
Wang	874	50 47	15 43	161.2	62.7	8.1	1.0
Kottbus	74	51 46	14 26	92.0	23.4	12.9	4.6
Eigenrieden	482	51 13	10 19	108.6	41.5	10.0	3.3
Rosslau	72	51 53	12 15	90.1	18.1	13.0	4.2
Borkum	11	53 36	06 40	48.3	13.1	11.2	6.8
Luneburg	20	53 15	10 24	89.8	21.1	12.6	4.1
Schoninghsdorf	27	52 43	07 05	93.9	12.9	12.7	3.4
Arnsberg	212	51 24	08 04	79.9	14.0	13.1	4.5
Aveleberg	216	49 45	06 42	81.0	11.8	13.6	4.1
Leverkusen	46	51 01	06 59	59.8	7.9	13.5	5.5
Mullenbach	410	51 04	07 35	95.3	25.4	11.1	3.9
Feldberg	878	50 14	08 27	134.8	58.8	8.1	2.3
Oberlahnstein	77	50 18	07 37	62.7	8.2	14.5	5.2
Annaberg	623	50 35	13 00	126.7	39.3	10.5	2.8
Zschadrass	220	51 09	12 50	84.1	23.4	12.6	4.8
Schmucke	910	50 39	10 47	157.1	76.4	7.3	1.3
Konigstuhl	563	49 24	08 44	101.9	34.3	10.4	4.4

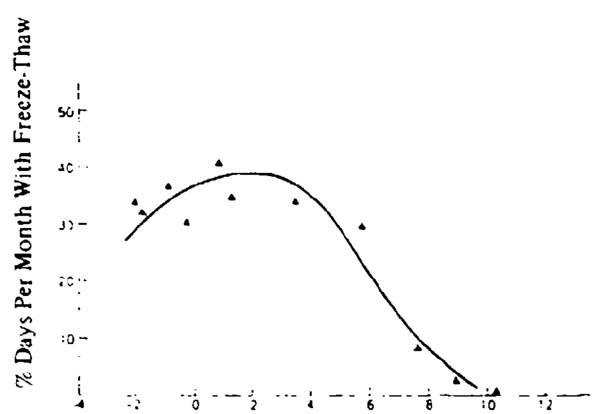
TABLE A3. Germany, Network 2 (52 Stations).

WOM 10XXX	Station Name	Altitude M	Latitude N	Longitude E	ANNUAL DAYS Frost (Min ≤ 0°C)	ANNUAL DAYS Ice (Max ≤ 0°C)	MEAN ANNUAL Daily Max(°C)	MEAN ANNUAL Daily Min(°C)
438	Kassel	200	51 19	09 29	78.5	23.6	12.5	4.8
488	Dresden-Neustadt	112	51 01	13 46	73.5	19.1	13.3	5.4
578	Fichtelberg	1220	50 26	12 57	181.1	100.6	5.7	0.8
470	Leipzig	125	51 18	12 23	81.8	22.9	12.9	5.1
569	Plaven	381	50 30	12 08	104.2	28.8	12.0	3.4
639	Dermstadt	148	49 53	08 41	71.6	15.1	13.6	5.6
532	Giessen	163	50 35	08 41	84.6	17.3	12.8	4.7
734	Heidelberg	118	49 25	08 42	54.8	13.5	13.9	6.5
727	Karlsruhe	125	49 00	08 26	75.0	17.1	14.0	5.9
729	Mannheim	100	49 29	08 27	66.9	15.9	13.8	6.1
657	Wertheim	147	49 46	09 31	89.4	18.7	13.4	4.5
934	Friedrichshafen	408	47 39	09 29	97.3	24.8	12.6	4.6
738	Stuttgart	267	48 47	09 10	68.0	18.3	13.8	5.6
838	Ulm	479	48 24	09 59	113.3	29.7	12.6	3.6
675	Bayreuth	364	49 57	11 34	114.6	27.2	12.5	3.2
685	Hof	477	50 19	11 55	130.9	33.4	11.4	1.7
763	Numberg	320	49 27	11 03	97.2	23.2	12.9	4.5
655	Wurzberg	179	49 48	09 56	81.3	18.9	13.5	4.9
893	Passau	310	48 34	13 28	100.5	24.8	12.5	4.3
776	Regensburg	343	49 00	12 05	107.3	29.8	12.6	3.4
852	Augsburg	502	48 22	10 54	100.8	30.9	12.4	4.3
962	Hohenpeissenberg	997	47 48	11 01	132.7	45.6	9.7	2.8
860	Ingolstadt	370	48 45	11 21	115.4	27.1	13.0	2.7
866	Munchen	538	48 08	11 34	105.3	30.8	12.5	4.0
961	Zugspitze	2962	47 25	10 59	313.0	232.0	-- 2.4	-7.3
185	Griefswald	7	54 06	13 23	83.7	21.2	11.4	4.4
279	Neustrelitz	75	53 22	13 04	102.4	25.0	12.0	3.9

TABLE A3. Germany, Network 2 (52 Stations). (Continued)

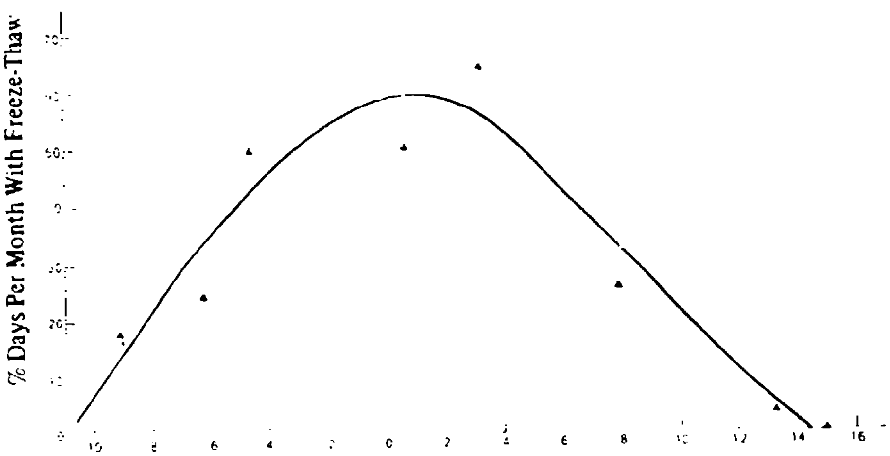
WOM 10XXX	Station Name	Altitude M	Latitude N	Longitude E	ANNUAL DAYS Frost (Min ≤ 0°C)	ANNUAL DAYS Ice (Max ≤ 0°C)	MEAN ANNUAL Daily Max(°C)	MEAN ANNUAL Daily Min(°C)
015	Helgoland	41	54 10	07 51	47.4	13.2	10.4	6.6
046	Kiel	47	54 19	10 08	77.5	22.8	10.9	5.0
035	Schleswig	35	54 32	09 34	80.6	18.7	11.2	4.4
147	Hamburg	29	53 38	10 02	67.1	20.3	11.5	5.7
499	Gorlitz	217	51 10	15 00	88.1	28.7	11.9	4.8
382	Berlin Dahlen	57	52 27	13 18	66.5	23.2	12.6	4.4
398	Frankfurt a.d.o.	57	52 20	14 35	68.2	27.8	12.5	4.4
380	Potsdam	82	52 23	13 04	67.2	25.3	12.8	4.4
453	Brocken	1150	51 48	10 37	100.5	83.5	5.0	-0.3
554	Erfut	218	50 58	11 04	102.0	28.8	12.4	3.5
359	Gardelegen	46	52 32	11 24	90.5	22.5	12.9	4.7
361	Magdeburg	58	52 08	11 38	77.5	21.3	13.5	5.1
343	Celle	39	52 38	10 06	84.8	20.0	12.5	4.4
202	Emden	8	53 22	07 12	66.6	16.1	11.7	5.4
338	Hannover	57	52 22	09 45	73.3	19.6	12.9	5.2
113	Norderney	4	53 43	07 09	53.9	12.0	11.2	6.0
128	Wilhelmshaver	8	53 32	08 09	63.6	18.0	11.4	5.6
122	Jever	12	53 35	07 54	71.4	17.7	12.0	5.0
215	Oldenburg	9	53 10	08 13	80.6	17.9	12.4	4.4
224	Bremen	9	53 05	08 47	71.9	17.9	12.2	5.4
129	Bremerhaven	6	53 33	08 34	69.7	15.8	12.0	5.2
501	Aachen	204	50 47	06 06	58.2	11.5	13.8	6.2
410	Essen/Mulheim	108	51 26	07 00	59.1	10.3	12.7	5.5
513	Koln	56	50 56	06 57	44.3	9.2	13.8	6.9
609	Trier	149	49 45	06 39	71.8	12.7	14.1	4.6

APPENDIX B. Additional Examples of Station Models (Empirical and Theoretical).



Mean Monthly Temperature °C

a. Akureyri, Iceland



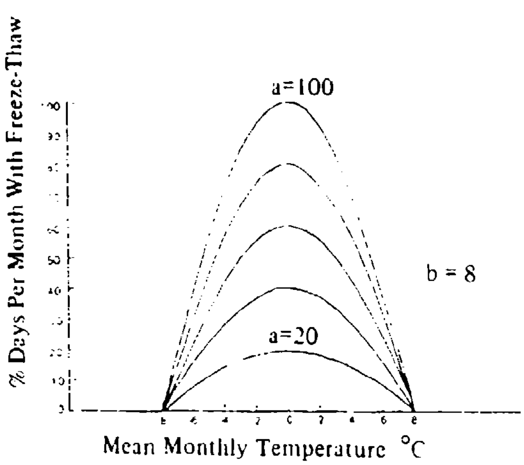
Mean Monthly Temperature °C

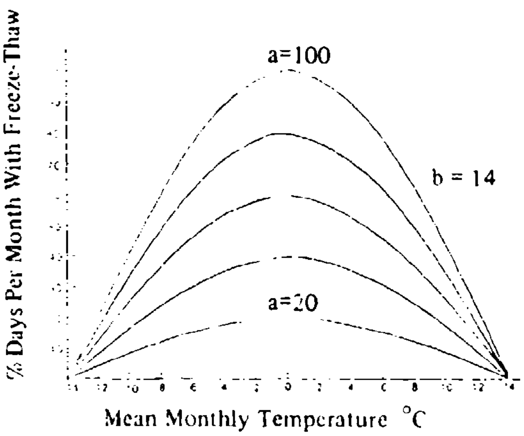
b. Sault Ste. Marie, Michigan

Note: Computed on 30-day basis.

FIGURE B1. Percent Days per Month with Freeze-Thaw per Mean Monthly Temperature: Empirical Plots.

APPENDIX B. (Continued)





Note: Computed on 30-day basis.

FIGURE B2. Percent Days per Month with Freeze-Thaw per Mean Monthly Temperature: Theoretical Plots.